IL NUOVO CIMENTO Online First Settembre-Ottobre 2006
DOI 10.1393/ncc/i2005-10193-2

A possible relationship between the Arctic Oscillation Index and atmosphere-triggered interannual long-wavelength gravitational variations(*)

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(ricevuto il 2 Settembre 2005; revisionato l'11 Aprile 2006; approvato il 10 Luglio 2006; pubblicato online il 13 Ottobre 2006)

Summary. — A host of geophysical processes contribute to temporal variations in the low-degree zonal harmonics of the Earth's gravity field. The present paper focuses on atmosphere-based mass redistributions using global surface pressure data from the NOAA Climate Diagnostics Center for the period 1980-2002. We computed atmosphere-triggered temporal variations of the Earth's low-degree zonal gravitational coefficients J_l ($l = 2:4$). Such atmosphere-triggered $\Delta J_l(t)$ are compared with the Arctic Oscillation Index (AOI) and with the observed $\Delta J_l(t)$ computed by the Italian Space Agency (ASI) so as to investigate a possible coupling. We show that there is a significant agreement between the AOI and atmosphere-triggered $\Delta J_l(t)$, as well as a particularly interesting correlation between the winter $\Delta J_l(t)$ series and the AOI active season series.

PACS 91.10.Qm – Harmonics of the gravity potential field; geopotential theory and determination.
PACS 91.50.Kx – Gravity and isostasy.
PACS 91.10.Vr – Ocean/Earth/atmosphere/hydrosphere/cryosphere interactions; mass balance.

1. – Introduction

Mass redistributions on or within the Earth will manifest themselves as temporal variations in the Earth's low-degree zonal gravitational coefficients J_l (l being the degree) [1]. A host of geophysical processes acting within a wide range of time-scales are responsible for such gravitational variations, including the postglacial rebound and present-day mass instabilities within the ice-caps. As discussed in [2,3] and [4], rapid shifts in glacial and oceanic mass appear to play the most significant role in gravitational variations, with the

(*) The authors of this paper have agreed to not receive the proofs for correction.

atmosphere likely making a smaller contribution. Focusing on the atmospheric contribution, the present paper investigates a possible relationship between atmosphere-triggered interannual gravitational variations and the Arctic Oscillation Index (AOI). According to [1], atmosphere-triggered interannual gravitational variations should be considered climatological in origin, since interannual mass redistributions within the atmosphere will show up as climate variability and changes. The Arctic Oscillation (AO), also known as Northern Annular Mode (NAM), has been recognized as the leading mode of variability of the extratropical Northern Hemisphere [5,6]. The AO was first defined by [7]: they used an Empirical Orthogonal Function (EOF) analysis of wintertime monthly-mean 1000 hPa geopotential anomalies to obtain this leading mode. Its pattern has a dominantly annular geographical structure with positive centers over both the Atlantic and Pacific Oceans and a negative center over the North Pole. The AO "rivals El Niño-Southern Oscillation (ENSO) in terms of its significance for understanding global climate variability and trends" [8]. Since the 1960s, the AO has experienced a trend toward a positive index, possibly related to climate change; the changes in the AO at the Earth's surface have been paralleled by a tendency for the high-latitude stratospheric polar vortex to be stronger and colder. In fact, the AO in the troposphere is strongly coupled to the strength of the stratospheric polar vortex, and stratospheric circulation anomalies are seen to propagate downward to the Earth's surface, where they are reflected as changes in the AO's magnitude and sign [9]: this relevant coupling between stratosphere and troposphere, occurring in the Northern winter (December through March), marks the AO active season. Various indices related to the AO mode have exhibited a pronounced drift toward the high index polarity during the past few decades, which is reflected in patterns of Sea Level Pressure (SLP), geopotential height, and surface air temperature [10] and [7].

2. – Theory and data set

The Earth's external gravity field is customarily expressed in a harmonic expansion in terms of the Stokes coefficients, as in [11]. Among them, the dimensionless "J" coefficients for the zonal harmonics are given by

$$J_l = -\frac{1}{MR^l}\int \rho(\overrightarrow{r})r^l P_l(\cos\vartheta)\mathrm{d}V\,. \tag{1}$$

In eq. (1), M and R are the Earth's total mass and mean radius; $\rho(\overrightarrow{r})$ is the mass density at position $\overrightarrow{r} = (r,\vartheta,\lambda)$, where r is the radial distance, ϑ is the colatitude, and λ is the east longitude; P_l is the Legendre function of degree l; and the integration is over the entire volume of the Earth (including the atmosphere), with volume element $\mathrm{d}V = r^2\sin\vartheta\mathrm{d}r\mathrm{d}\vartheta\mathrm{d}\lambda$. Note that J_l are not normalized: they are related to the normalized Stokes coefficients C_{l0} by

$$J_l = -(2l+1)^{1/2}C_{l0}\,. \tag{2}$$

Any temporal variation in $\rho(\overrightarrow{r})$ will, according to eq. (1), give rise to a temporal variation in J_l, $\Delta J_l(t)$. For mass redistributions in the atmosphere (where $r = R$) in an Eulerian description and assuming a vertical hydrostatic profile for the atmosphere, it can be shown that

$$\Delta J_l(t) = -\frac{(1+k_l^{'})}{Mg} R^2 \int \Delta p(\sigma, t) P_l(\cos\vartheta) \mathrm{d}\sigma\,, \tag{3}$$

where g is the average gravitational acceleration, Δp the departure of the sea level pressure (SLP data) from the mean state, sigma the solid angle representing (ϑ, λ), and the integration is over the unit sphere with surface element $\mathrm{d}\sigma = \sin\vartheta \mathrm{d}\vartheta \mathrm{d}\lambda$. The Earth's load Love numbers, $k_l^{'}$, are taken from [12]: $k_1^{'} = -0.31, k_2^{'} = -0.20, k_3^{'} = -0.13$, etc. The factor $(1 + k_l^{'})$ accounts for the elastic yielding effect of the solid Earth under surface loading/unloading. The P_l Legendre function serves as a geographical weighting function in the surface integral. By means of harmonic analysis, for the given function $\sum_{n,m} T_{nm} Y_{nm}$, which represents the harmonic expansion of the Δp data defined on the σ sphere, at a fixed time, it can be demonstrated that

$$\Delta J_l(t) = -\frac{(1+k_l^{'})}{Mg} R^2 \int_\sigma \sum_{n,m} T_{nm} Y_{nm}(\vartheta, \lambda) P_l(\cos\vartheta) \mathrm{d}\sigma\,, \tag{4}$$

$$\Delta J_l(t) = -4\pi \frac{(1+k_l^{'})}{Mg} R^2 T_{l0}\,, \tag{5}$$

where T_{l0} are the zonal harmonic coefficients resulting from the harmonic analysis of the Δp data. $\Delta J_l(t)$ provide a complete picture of the atmosphere-triggered gravitational variations. The Δp data were obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis [13], obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostics Center (CDC). The data are gridded on a 2.5° lat by 2.5° long mesh. We used the 1980-2002 Sea Level Pressure (SLP) series data set, since SLP data provide the best dynamical information for the AO. Bimonthly records of the series were considered.

The AO index was obtained from `tao.atmos.washington.edu/ao/`.

We also used observed $\Delta J_l(t)$ records, computed by means of Satellite Laser Ranging (SLR) techniques by the Italian Space Agency (ASI), as in [14].

3. – Results

The atmosphere-related $\Delta J_2(t)$, $\Delta J_3(t)$ and $\Delta J_4(t)$ series are shown in fig. 1. We observe that there is a drift toward a positive value in $\Delta J_2(t)$ and $\Delta J_4(t)$ series over the last two decades, whereas $\Delta J_3(t)$ does not show any significant trend. The positive trends in $\Delta J_2(t)$ and $\Delta J_4(t)$ series have been proved to be significant by means of the Mann-Kendall non-parametric test (significance level greater than 99%) [15].

As in [1] and [4], we agree that the climate system might play an interesting role in short-term gravitational perturbations, and that climate variability and change might be mirrored by interannual atmosphere-related gravitational variations. We thus correlated atmosphere-triggered $\Delta J_l(t)$ computed in our research with observed $\Delta J_l(t)$ computed by the Italian Space Agency (ASI) as in [14]. ASI-observed $\Delta J_l(t)$ series contain all non-secular contributions to gravitational variations: they include atmospheric and the still poorly known hydrospheric and short-term cryospheric contributions. Our aim was to estimate how much of the ASI-observed $\Delta J_l(t)$ could actually be considered as triggered,

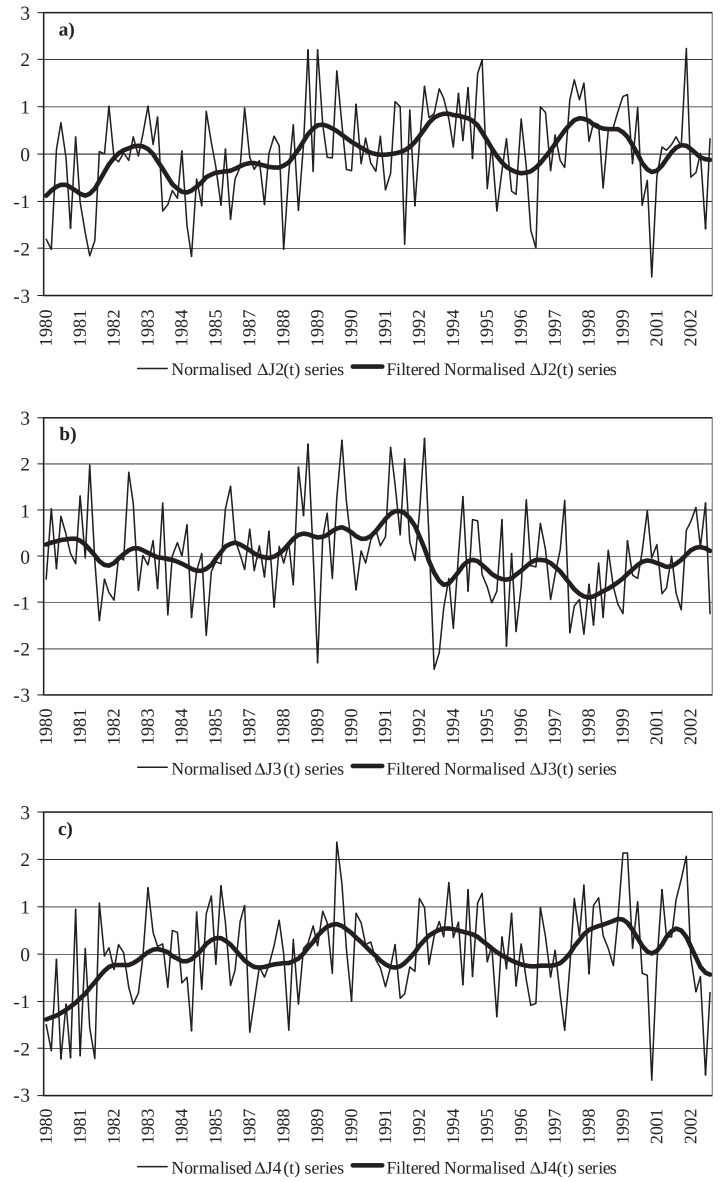

Fig. 1. – Variation of the zonal $\Delta J_2(t)$ (a), $\Delta J_3(t)$ (b) and $\Delta J_4(t)$ (c) coefficients (in units of 10^{-10}) for the time interval 1980-2002. The thick lines denote 6-month σ Gaussian low-pass filtered curves for the $\Delta J_l(t)$ records.

or at least "contaminated", by interannual mass redistributions within the atmosphere. The results showed that there is a significant agreement between ASI-observed $\Delta J_2(t)$ and atmospheric $\Delta J_2(t)$ ($r = 0.41$, significance level greater than 99%). Less important correlations have been found between ASI-observed $\Delta J_{\mathrm{odd}}(t)$ and atmosphere-related $\Delta J_3(t)$ ($r = 0.20$), as well as between ASI-observed $\Delta J_4(t)$ and atmospheric $\Delta J_4(t)$ ($r = 0.22$).

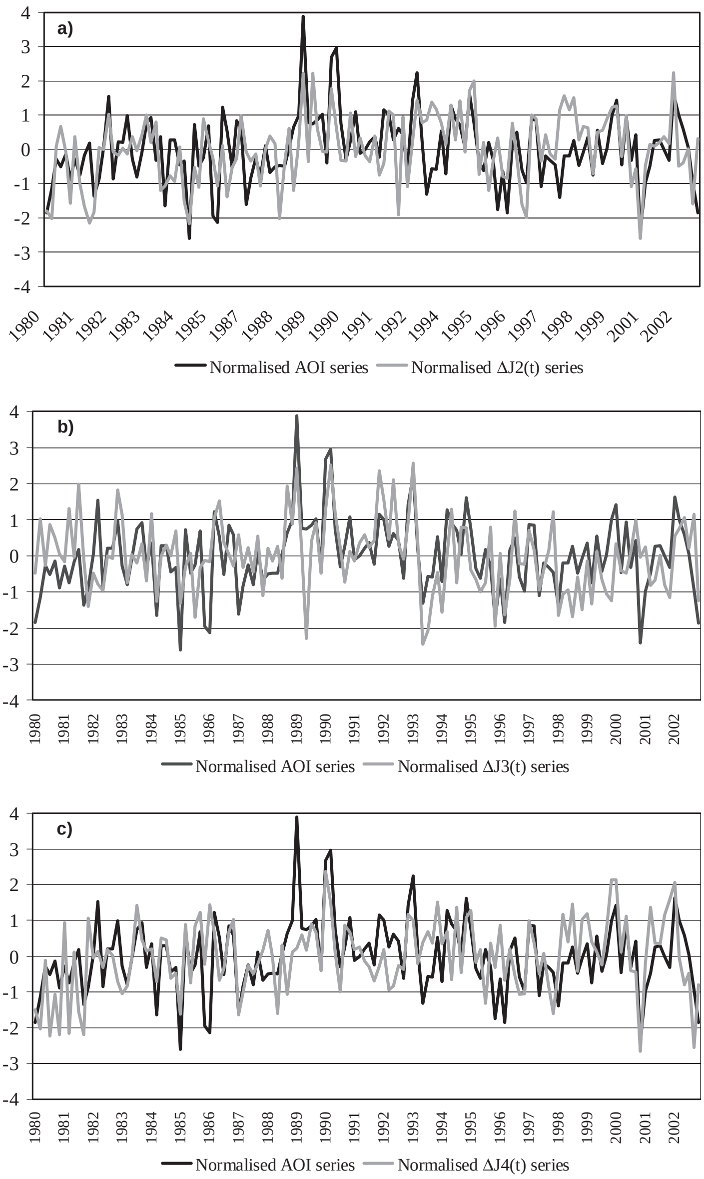

Fig. 2. – Correlations between atmosphere-triggered $\Delta J_2(t)$ (a), $\Delta J_3(t)$ (b) and $\Delta J_4(t)$ (c) series and the AOI: 1980-2002. All series are normalized. Correlation coefficients are invariably $r = 0.51$.

The atmosphere-triggered interannual gravitational variations might be related to and coupled with the most considerable climatological phenomena which have been observed and computed over the last few decades, *i.e.* El Niño-Southern Oscillation (as in [4]) and the Arctic Oscillation. In other words, mass redistributions within the atmosphere related to ENSO and the AO phenomena might show a discernible "gravitational signature", in terms of atmospheric $\Delta J_l(t)$, as can also be argued by comparing and correlating

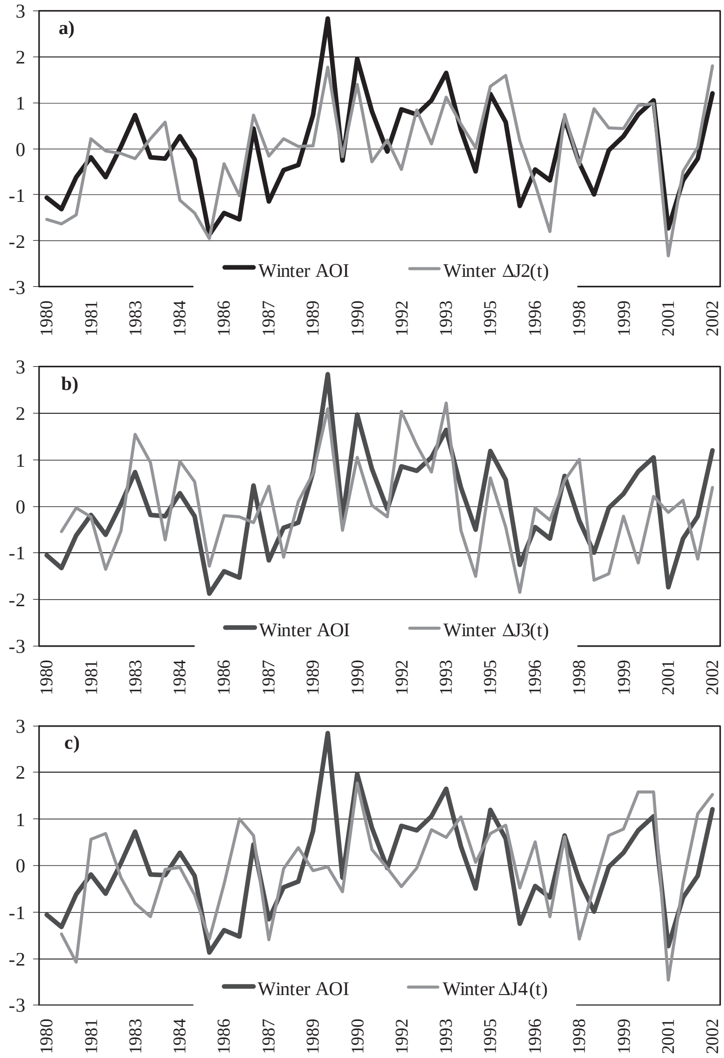

Fig. 3. – Correlations between atmosphere-triggered $\Delta J_2(t)$ (a), $\Delta J_3(t)$ (b) and $\Delta J_4(t)$ (c) winter series and the winter AOI: 1980-2002. All series are normalized.

climatological indices like the Southern Oscillation Index (SOI) and the AOI and the atmosphere-triggered $\Delta J_l(t)$.

The correlation between SOI series and $\Delta J_l(t)$ is rather low. $\Delta J_2(t)$ and $\Delta J_4(t)$ have negative correlation coefficients with the SOI series ($r = -0.12$ and $r = -0.14$, respectively), whereas $\Delta J_3(t)$ displays a positive $r = 0.16$. Negative values of the SOI stand for an El Niño phenomenon, whereas positive values of the SOI indicate a La Niña event. Most El Niño episodes seem to be paralleled by a positive gravitational signature, in terms of $\Delta J_2(t)$ and $\Delta J_4(t)$, whereas La Niña events seem to be mirrored by a negative signature. However, the correlation coefficients between the SOI and the atmosphere-triggered $\Delta J_l(t)$ series are so low that the described results can be hardly considered as

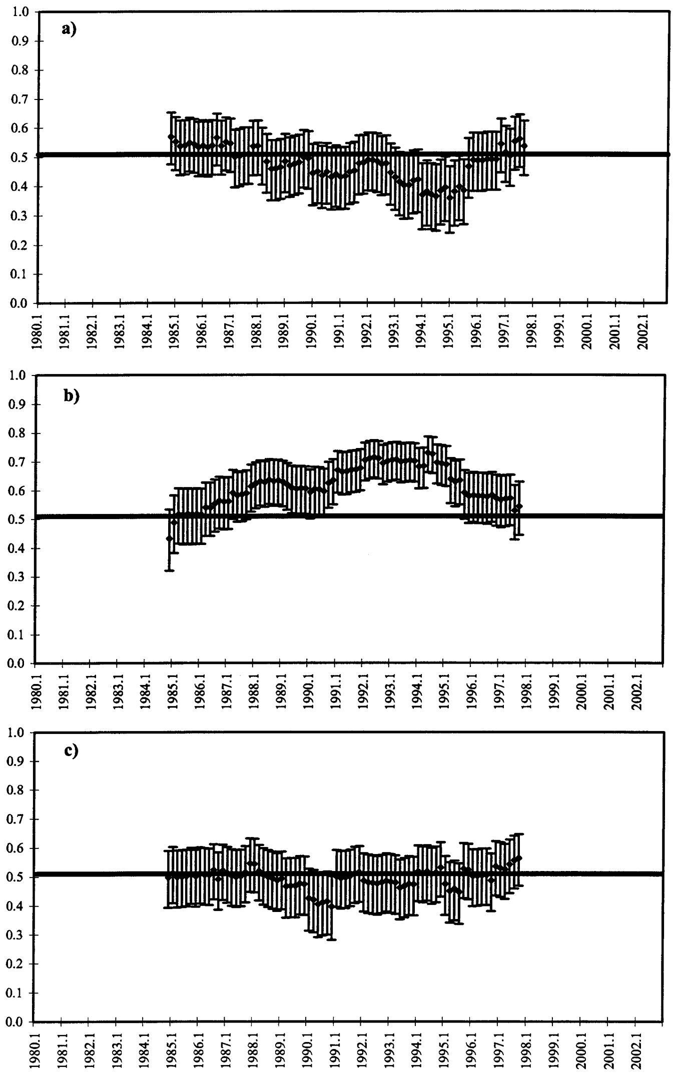

Fig. 4. – Running correlation coefficients ρ between atmosphere-triggered $\Delta J_2(t)$ (a), $\Delta J_3(t)$ (b) and $\Delta J_4(t)$ (c) series and the AOI. The coefficients are obtained with a 122-month window centered over the 31st two-month period, so they concern periods of 10 years + 2 months. The window is shifted from two-month period 31 (January-February 1986) to two-month period 108 (November-December 1997) with a bimonthly step. Error bars denote the $\rho \pm \sigma$ limits. The thick line denotes the linear correlation coefficient r calculated over the entire period.

conclusive or significant.

Such a relatively poor agreement between the SOI series and atmosphere-triggered $\Delta J_l(t)$, also investigated in [4], becomes definitely more solid when we correlate our $\Delta J_l(t)$ gravitational series and the AOI series, as shown in fig. 2: the linear correlation coefficient reaches $r = 0.51$ for $\Delta J_2(t)$, $\Delta J_3(t)$ and $\Delta J_4(t)$, invariably displaying a significance level greater than 99%.

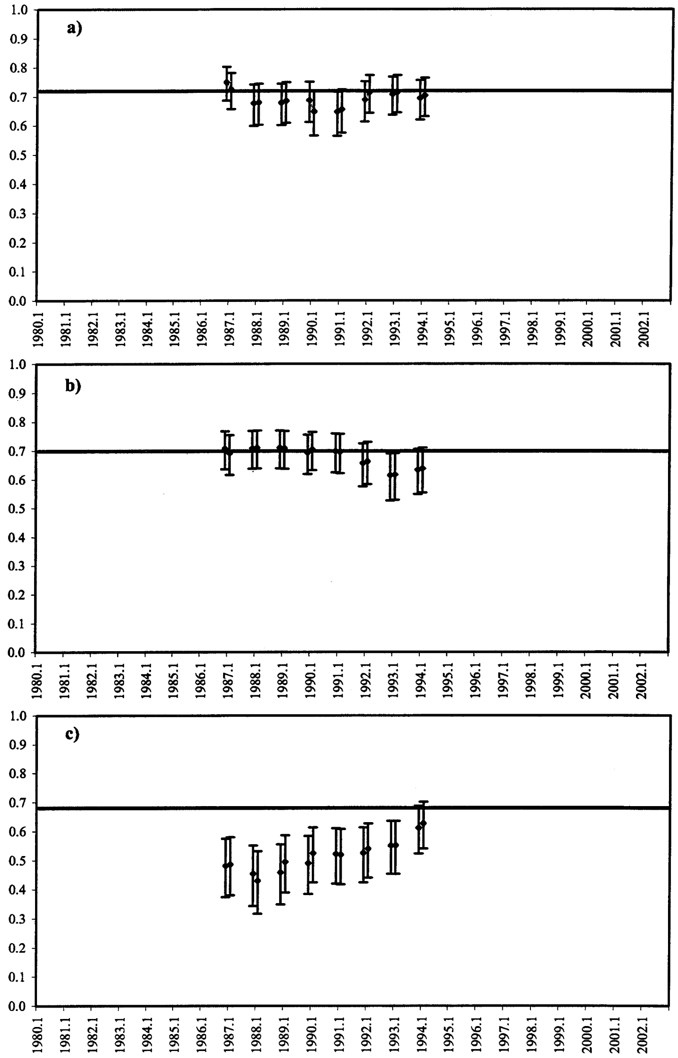

Fig. 5. – Running correlation coefficients ρ between atmosphere-triggered $\Delta J_2(t)$ (a), $\Delta J_3(t)$ (b) and $\Delta J_4(t)$ (c) winter series and the winter AOI. Here winter is considered as being composed by the November-December and January-February two-month periods. The coefficients are obtained with a 21-data window centered over the 11th value. The window is shifted from datum 11 (January-February 1986) to datum 36 (November-December 1997). Error bars denote the $\rho \pm \sigma$ limits. The thick line denotes the linear correlation coefficient r calculated over the entire period.

The agreement between the AOI and the $\Delta J_l(t)$ series is particularly high in the AOI active season (December through March), as shown in fig. 3a. In fact, the active season AOI series, when correlated with its winter analogue for atmospheric $\Delta J_2(t)$, displays a correlation coefficient $r = 0.72$. Such a good correlation is confirmed for both winter $\Delta J_3(t)$ and $\Delta J_4(t)$ series, shown in figs. 3b and 3c, that display, respectively, $r = 0.70$ and $r = 0.68$. In other seasons, the correlation coefficients between the AOI and $\Delta J_2(t)$

are lower, reaching $r = 0.31$ in July through October, and $r = 0.36$ in March through June. Nevertheless, March through June correlations between AOI and $\Delta J_3(t)$ as well as $\Delta J_4(t)$ series are still remarkable ($r = 0.54$ and $r = 0.47$, respectively), and July through October correlations are considerable as far as $\Delta J_4(t)$ is concerned ($r = 0.56$), and quite low for $\Delta J_3(t)$ ($r = 0.21$).

In order to verify whether the correlation coefficients r of the 1980-2002 period are genuinely representative of the whole investigated period, we performed a running correlation analysis between the atmosphere-triggered $\Delta J_l(t)$ and the AOI series using a 10-year moving window with a bimonthly step. The results are shown in figs. 4 and 5, where the moving correlation coefficients ρ are shown together with their standard errors ($\rho \pm \sigma$), and compared with the correlation coefficients r calculated over the entire 1980-2002 period.

Figure 4a (concerning correlation between the atmosphere-triggered $\Delta J_2(t)$ and the AOI series) gives evidence that, even though some periods like the ones centered around 1985 and 1997 display higher correlation coefficients than the other ones (*e. g.*, the one centered around 1995), the value r representative of the entire period is almost invariably contained within the $\rho \pm \sigma$ limits. Moreover, if we search for results significant at a 95% level, we find that in no cases the difference between the correlation coefficients ρ computed with a 10-year moving window and the correlation coefficient r calculated over the entire 1980-2002 period is significant. We can observe similar results if we consider the result described running correlation procedure between the atmosphere-triggered $\Delta J_4(t)$ and the AOI series, as shown in fig. 4c. As far as we consider the results of the running correlation between the atmosphere-triggered $\Delta J_3(t)$ and the AOI series, as shown in fig. 4b, the differences between the running correlation coefficients ρ and the linear correlation coefficient r calculated over the entire investigated period seem more important, especially if we observe the period centered over 1991-1995. In fact, such period displays rather high values, the highest one being $\rho = 0.73$ for the period centered in the third two-month period of 1994. However, if we likewise consider the 95%-confidence limits of the correlation coefficient r calculated over the entire period, we can observe that not even such apparently higher difference is particularly significant, as the 10-year 95%-confidence lower limit of ρ appears to be encompassed in the higher 95%-confidence limit of r.

Figure 5 shows the same running correlation analysis discussed above and performed for the winter atmosphere-triggered and the active season AOI series. Even though it would be possible to make similar considerations about the results, the evaluation of the true significance of the relationships between the running correlation coefficients ρ and the linear correlation coefficient r is even more problematic due to the narrowness of the winter data-set. However it may be interesting to highlight that, as far as correlations involving atmosphere-triggered $\Delta J_2(t)$ and $\Delta J_3(t)$ are considered (figs. 5a and 5b), the value of r is always within the $\rho \pm \sigma$ limits; on the other hand, if we observe the running correlation analysis performed for atmosphere-triggered $\Delta J_4(t)$ and shown in fig. 5c, coefficients ρ are generally lower than the linear coefficient r.

4. – Discussion and conclusions

The considerable correlation between the AOI and $\Delta J_l(t)$ series during the AO active season is probably related to the fact that the AO active season exhibits significant interactions between the stratosphere and the troposphere, with remarkable exchanges and redistributions of air masses through the tropopause. Kodera *et al.* [16] observed that strong upper-stratospheric westerlies in December tend to propagate poleward and downward, so that tropospheric westerlies at high latitudes are stronger during the following February. The mechanism for downward propagation of large stratospheric anomalies and the implications of large stratospheric anomalies as precursors to changes in tropospheric weather patterns were discussed by [9].

In conclusion, the Arctic Oscillation, being the leading mode of climate change and variability in the Northern Hemisphere, seems to play a significant role in interannual coupling processes between atmosphere-climate and gravity. We found that AO-related atmospheric dynamics have a remarkable contribution, yet they cannot fully explain the atmosphere-triggered interannual variations of the lowest zonal harmonics J_2, J_3 and J_4. It is possible that better and more complete results are obtained if a wider spectrum of climatological phenomena (such as, *e.g.*, the Southern Annular Mode or Antarctic Oscillation) is somehow taken into account. This interesting and possible relationship of causality obviously calls for further investigation, as it would have significant impacts both on climatological analyses related to the annular modes and on realistic constraints for global rheological models of the Earth [17].

It will also be necessary to take into account the effects of the hydrosphere itself, and also of the coupling between the atmosphere and the hydrosphere, as the effect of the oceans' barometric response may be not trivial nor negligible. The inclusion of these factors could probably help in overcoming the most critical weak point of the research which consists in the rather low correlation of the pressure-field-calculated $\Delta J_l(t)$ records and the ASI-computed series: even if they are correlated at a highly significant level, the observed gravitational record only give evidence of a very small fraction of the atmosphere-triggered gravity variability.

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